EECS130
Integrated Circuit Devices

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9/11/2007

<u>Semiconductor Fundamentals</u>

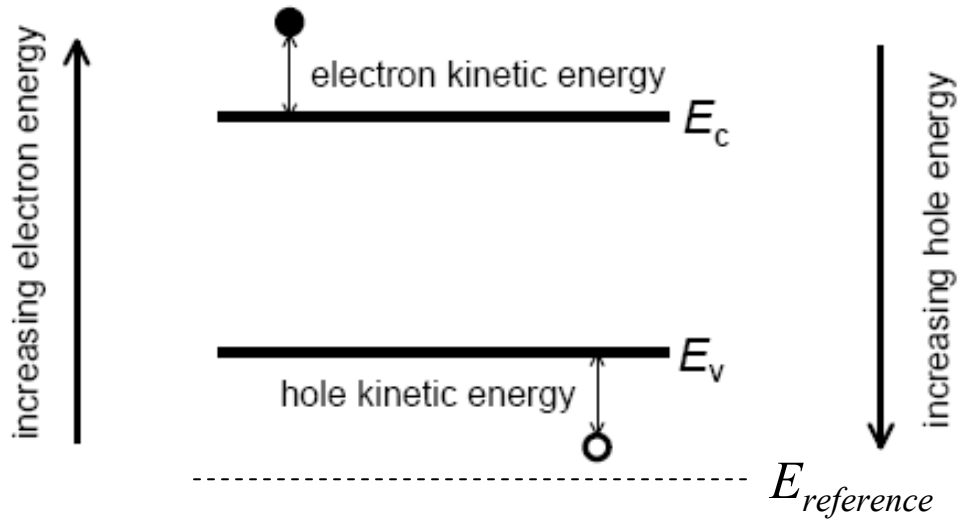
<u>Lecture 5</u>

Reading: Chapter 3

Announcements

- 1st HW due….. right now….
- 2nd HW due next Tuesday
- Professor Javey's OH for tomorrow is cancelled. He will have an extra OH next week.

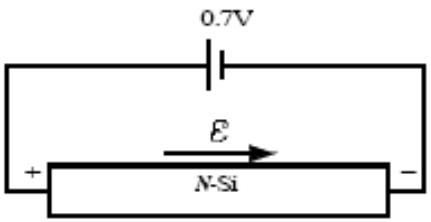
Band Diagram: Potential *vs.* Kinetic Energy

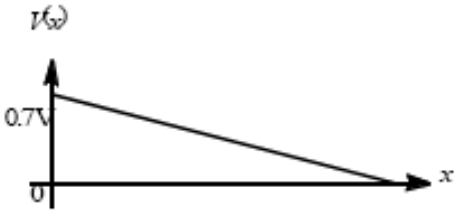


E_c represents the electron potential energy:

$$\text{P.E.} = E_c - E_{\text{reference}}$$

Electrostatic Potential *V*



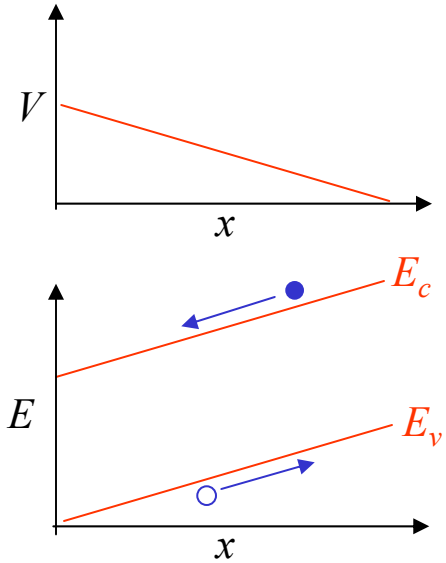


- Potential energy of a $-q$ charged particle is related to the electrostatic potential $V(x)$:

E_c and E_v vary in the opposite direction from the voltage. That is, E_c and E_v are higher where the voltage is lower.

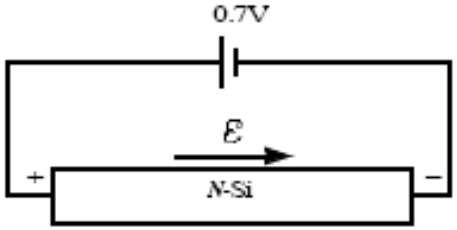
$$\text{P.E.} = -qV$$

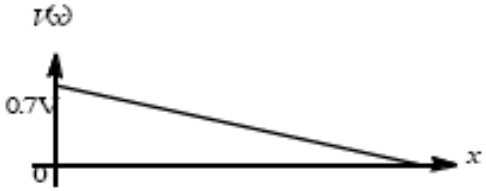
$$E_c - E_{reference} = -qV$$



Variation in E_c with position is called <u>band bending</u>

Electric Field $\mathcal{E}$

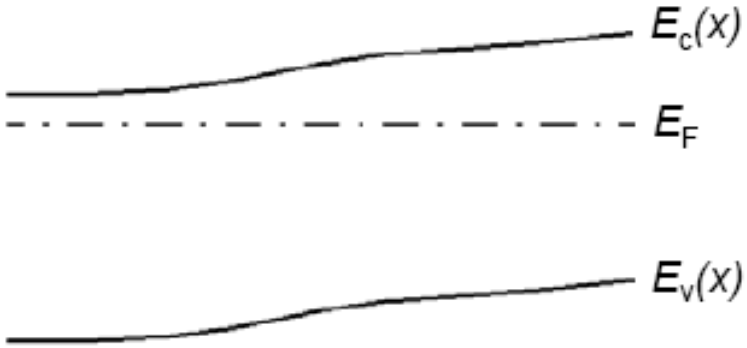




$$\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

Non-Uniformly-Doped Semiconductor

- The position of E_F relative to the band edges is determined by the carrier concentrations, which is determined by the dopant concentrations.
- **In equilibrium, E_F is constant**; therefore, the band energies vary with position:



- In equilibrium, there is no net flow of electrons or holes

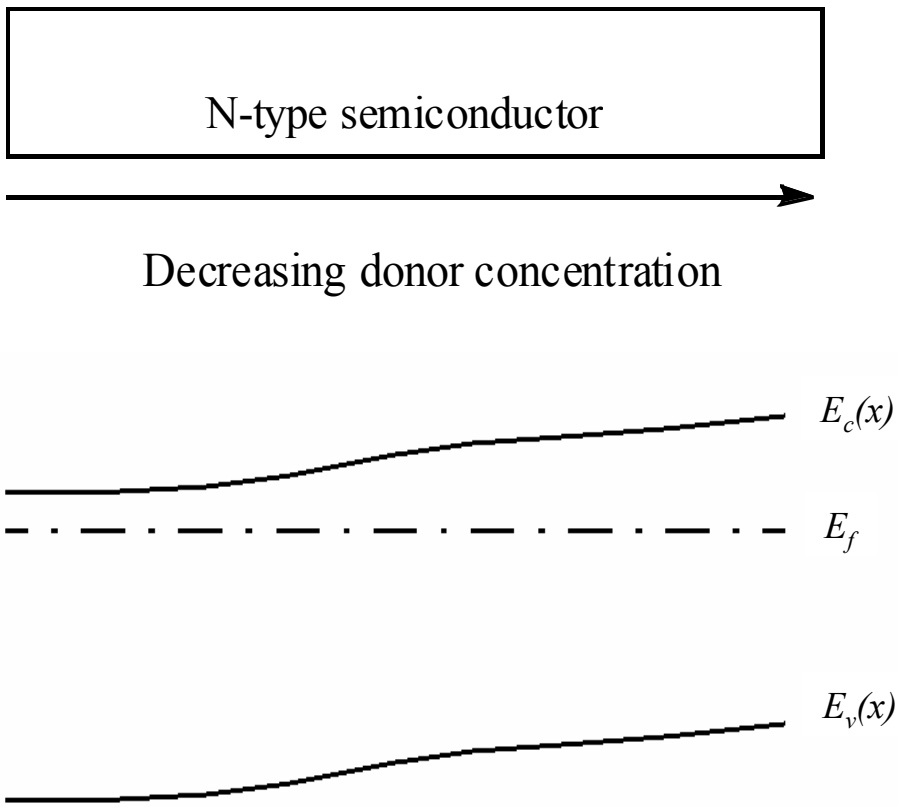
$$J_N = 0 \quad \text{and} \quad J_P = 0$$

➔ The drift and diffusion current components must balance each other exactly. (A built-in electric field exists, such that the drift current exactly cancels out the diffusion current due to the concentration gradient.)

$$J_N = qn\mu_n\mathcal{E} + qD_N\frac{dn}{dx} = 0$$

Einstein Relationship between D and μ

Consider a piece of non-uniformly doped semiconductor.



$$n = N_c e^{-(E_c - E_f)/kT}$$

$$\frac{dn}{dx} = -\frac{N_c}{kT} e^{-(E_c - E_f)/kT} \frac{dE_c}{dx}$$

$$= -\frac{n}{kT} \frac{dE_c}{dx}$$

$$= -\frac{n}{kT} q \mathcal{E}$$

Einstein Relationship between D and μ

$$\frac{dn}{dx} = -\frac{n}{kT} q\mathcal{E}$$

$$J_n = qn\mu_n\mathcal{E} + qD_n \frac{dn}{dx} = 0 \quad \text{at equilibrium.}$$

$$0 = qn\mu_n\mathcal{E} - qn\frac{qD_n}{kT}\mathcal{E}$$

$$\boxed{D_n = \frac{kT}{q}\mu_n} \quad \text{Similarly,} \quad \boxed{D_p = \frac{kT}{q}\mu_p}$$

These are known as the <u>Einstein relationship</u>.

EXAMPLE: Diffusion Constant

What is the hole diffusion constant in a piece of silicon with $\mu_p = 410\ cm^2\ V^{-1}s^{-1}$?

Solution:

$$D_p = \left(\frac{kT}{q}\right)\mu_p = (26\,\mathrm{mV})\cdot 410\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1} = 11\,\mathrm{cm}^2/\mathrm{s}$$

Remember: kT/q = 26 mV at room temperature.

Generation and Recombination

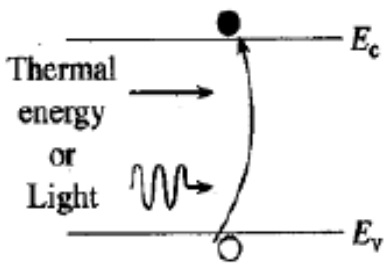
- Generation:

- Recombination:

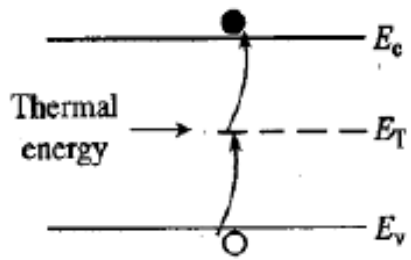
- Recombination and Generation processes act to change the carrier concentrations, and thereby indirectly affect current flow

Generation Processes

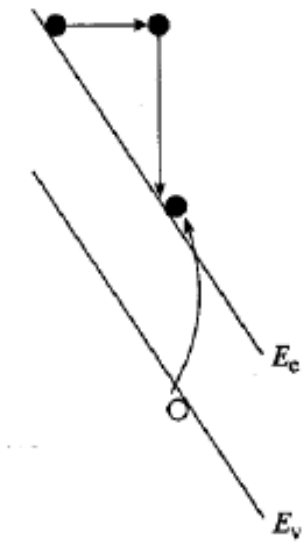
Band-to-Band



R-G Center

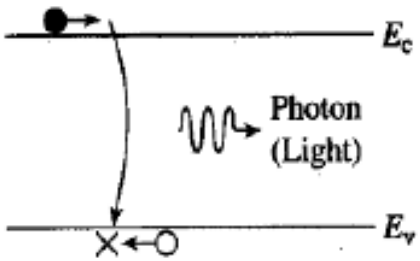


Impact Ionization

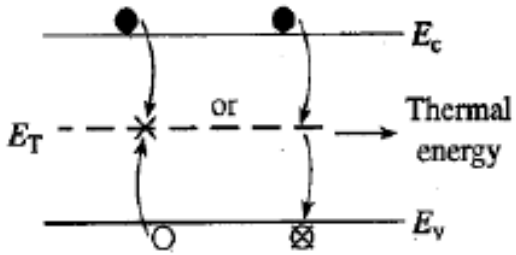


Recombination Processes

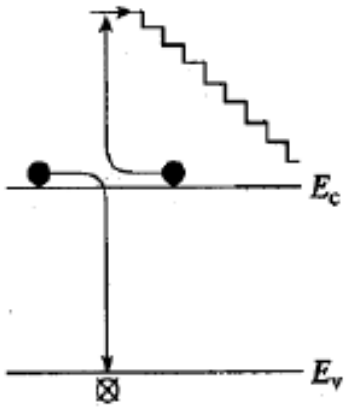
Direct



R-G Center



Auger



Excess Carriers and Charge Neutrality

Equilibrium Excess

$$n \equiv n_0 + \Delta n$$
$$p \equiv p_0 + \Delta p$$

Charge neutrality:

$$\Delta n = \Delta p$$

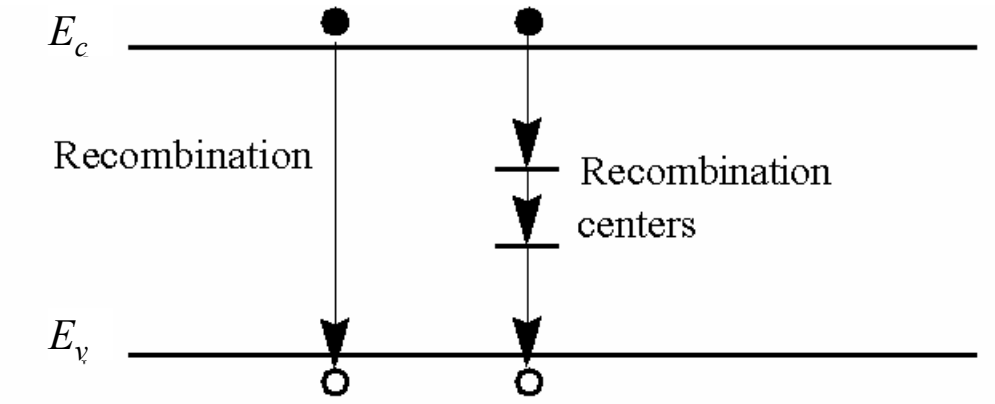
If not neutral, then built in field causes drift until neutrality is achieved

Recombination Lifetime

Assume light generates Δn and Δp. If the light is suddenly turned off, Δn and Δp decay with time until they become zero. The process of decay is called ***recombination.*** The time constant of decay is the ***recombination time*** or ***carrier lifetime,*** $\boldsymbol{\tau}$. Recombination is nature's way of restoring equilibrium ($\Delta n = \Delta p = 0$).

Recombination Lifetime

τ ranges from 1ns to 1ms in Si and depends on the density of metal impurities (contaminants) such as Au and Pt. These ***deep traps*** capture electrons or holes to facilitate recombination and are called ***recombination centers.***



Rate of recombination ($s^{-1}cm^{-3}$)

Consider recombination only.

$$\frac{dn}{dt} = -\frac{\Delta n}{\tau}$$

$$\Delta n = \Delta p$$

$$\frac{dn}{dt} = -\frac{\Delta n}{\tau} = -\frac{\Delta p}{\tau} = \frac{dp}{dt}$$

EXAMPLE: Photoconductors

A bar of Si is doped with boron at $10^{15}cm^{-3}$. It is exposed to light such that electron-hole pairs are generated throughout the volume of the bar at the rate of $10^{20}/s \cdot cm^3$. The recombination lifetime is $10\mu s$. What are (a) p_0, (b) n_0, (c) Δp, (d) Δn, (e) p, (f) n, and (g) the np product?

EXAMPLE: Photoconductors

Solution:

(a) What is p_0?

$p_0 = N_a = 10^{15}\ \text{cm}^{-3}$

(b) What is n_0 ?

$n_0 = n_i^2/p_0 = 10^5\ \text{cm}^{-3}$

(c) What is Δp?

In steady-state, the rate of generation is equal to the rate of recombination.

$$10^{20}/\text{s-cm}^3 = \Delta p/\tau$$

$$\therefore\ \Delta p = 10^{20}/\text{s-cm}^3 \cdot 10^{-5}\text{s} = 10^{15}\ \text{cm}^{-3}$$

EXAMPLE: Photoconductors

(d) What is Δn?

$\Delta n = \Delta p = 10^{15}\ \text{cm}^{-3}$

(e) What is p?

$p = p_0 + \Delta p = 10^{15}\text{cm}^{-3} + 10^{15}\text{cm}^{-3} = 2\times10^{15}\text{cm}^{-3}$

(f) What is n?

$n = n_0 + \Delta n = 10^{5}\text{cm}^{-3} + 10^{15}\text{cm}^{-3} \sim 10^{15}\text{cm}^{-3}$ *since* $n_0 << \Delta n$

(g) What is np?

$np \sim 2\times10^{15}\text{cm}^{-3} \cdot 10^{15}\text{cm}^{-3} = 2\times10^{30}\text{cm}^{-6} >> n_i^2 = 10^{20}\text{cm}^{-6}$.

The np product can be very different from n_i^2.

Quasi-equilibrium and Quasi-Fermi Levels

Whenever $\Delta n = \Delta p \neq 0$, $np \neq n_i^2$. However, we would like to preserve and use the relations:

$$n = N_c e^{-(E_c - E_f)/kT}$$

$$p = N_v e^{-(E_f - E_v)/kT}$$

But these equations lead to $np = n_i^2$. The solution is to introduce two ***quasi-Fermi levels*** E_{fn} and E_{fp} such that

$$n = N_c e^{-(E_c - E_{fn})/kT}$$

$$p = N_v e^{-(E_{fp} - E_v)/kT}$$

Even when electrons and holes are not at equilibrium, *within each group* the carriers are usually at equilibrium. Electrons are closely linked to other electrons but only loosely to holes.

Example: Quasi-Fermi Levels

Consider a Si sample with $N_D = 10^{17}$ cm^{-3} and $\Delta n = \Delta p = 10^{14}$ cm^{-3}.

(a) Find n:

$$n = n_0 + \Delta n = N_D + \Delta n \approx 10^{17} \text{ cm}^{-3}$$

(b) Find p:

$$p = p_0 + \Delta p = (n_i^2 / N_D) + \Delta p \approx 10^{14} \text{ cm}^{-3}$$

(c) Find the np product:

$$np \approx 10^{17} \times 10^{14} = 10^{31} \text{ cm}^{-6} >> n_i^2$$

(d) Find F_N:

$n = 10^{17}\ \text{cm}^{-3} = N_c e^{-(E_c - F_N)/kT}$

$E_c - F_N = kT \times ln(N_c/10^{17})$

$= 0.026\ \text{eV} \times ln(2.8\times10^{19}/10^{17})$

$= 0.15\ \text{eV}$

(e) Find F_P:

$p = 10^{14}\ \text{cm}^{-3} = N_v e^{-(F_P - E_v)/kT}$

$F_P - E_v = kT \times ln(N_v/10^{17})$

$= 0.026\ \text{eV} \times \ln(10^{19}/10^{14})$

$= 0.30\ \text{eV}$

Chapter Summary

$$v_p = \mu_p \mathcal{E}$$

$$v_n = -\mu_n \mathcal{E}$$

$$J_{p,drift} = qp\mu_p \mathcal{E}$$

$$J_{n,drift} = qn\mu_n \mathcal{E}$$

$$J_{n,diffusion} = qD_n \frac{dn}{dx}$$

$$J_{p,diffusion} = -qD_p \frac{dp}{dx}$$

$$D_n = \frac{kT}{q}\mu_n$$

$$D_p = \frac{kT}{q}\mu_p$$

Chapter Summary

τ is the recombination lifetime.

n' and p' are the ***excess carrier concentrations***.

$$n = n_0 + \Delta n$$
$$p = p_0 + \Delta p$$

Charge neutrality requires $\Delta n = \Delta p$.

$$\textit{rate of recombination} = \Delta n/\tau = \Delta p/\tau$$

E_{fn} and E_{fp} are the quasi-Fermi levels of electrons and holes.

$$n = N_c e^{-(E_c - E_{fn})/kT}$$
$$p = N_v e^{-(E_{fp} - E_v)/kT}$$